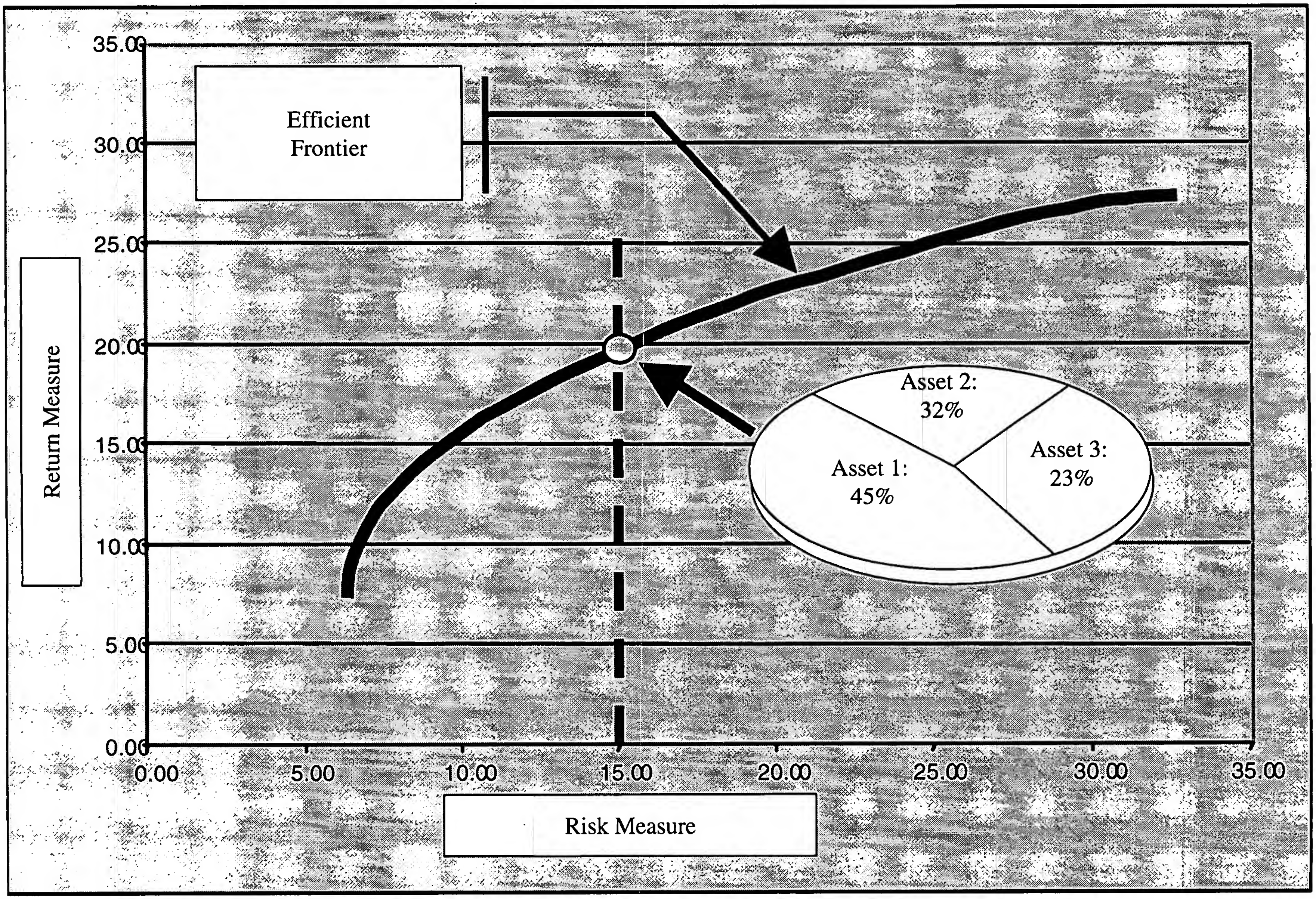
Fig. 1

BACKGROUND ART



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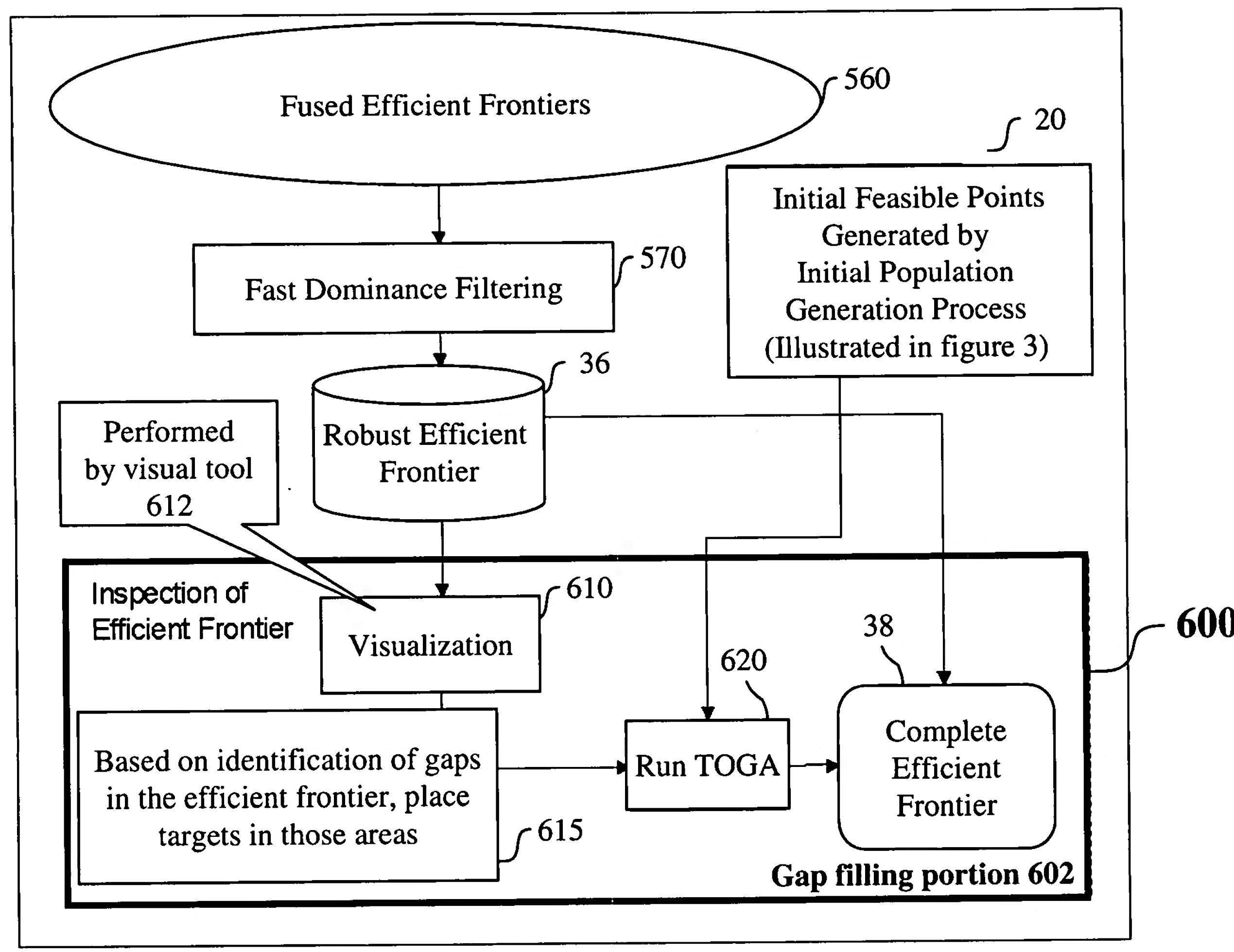
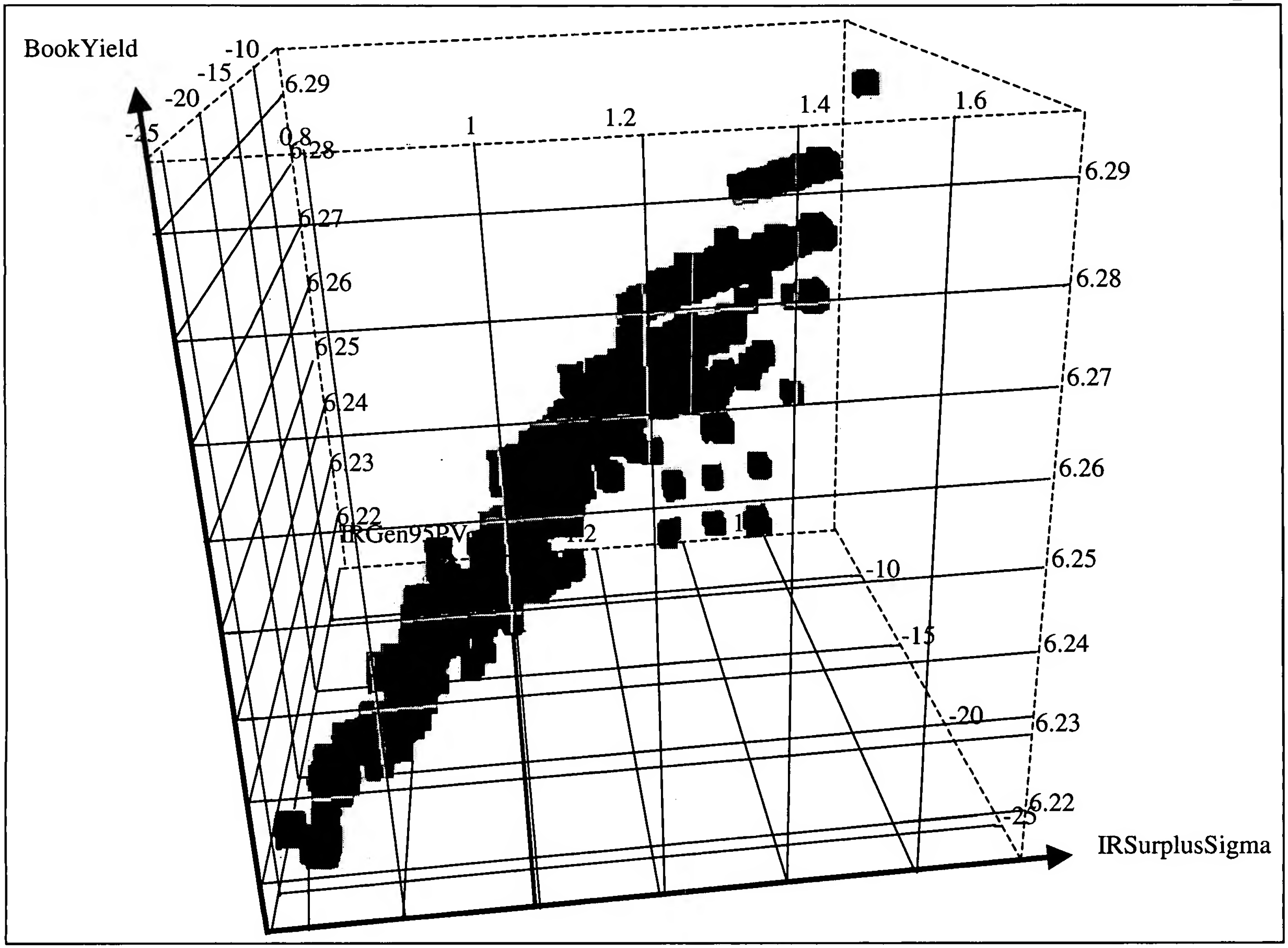


Fig. 12

Process to interactively fill any gaps in the identified efficient frontier

Fig. 13

Efficient Frontier in a 3D View



EXAMPLE OF PARALLEL COORDINATE PLOT

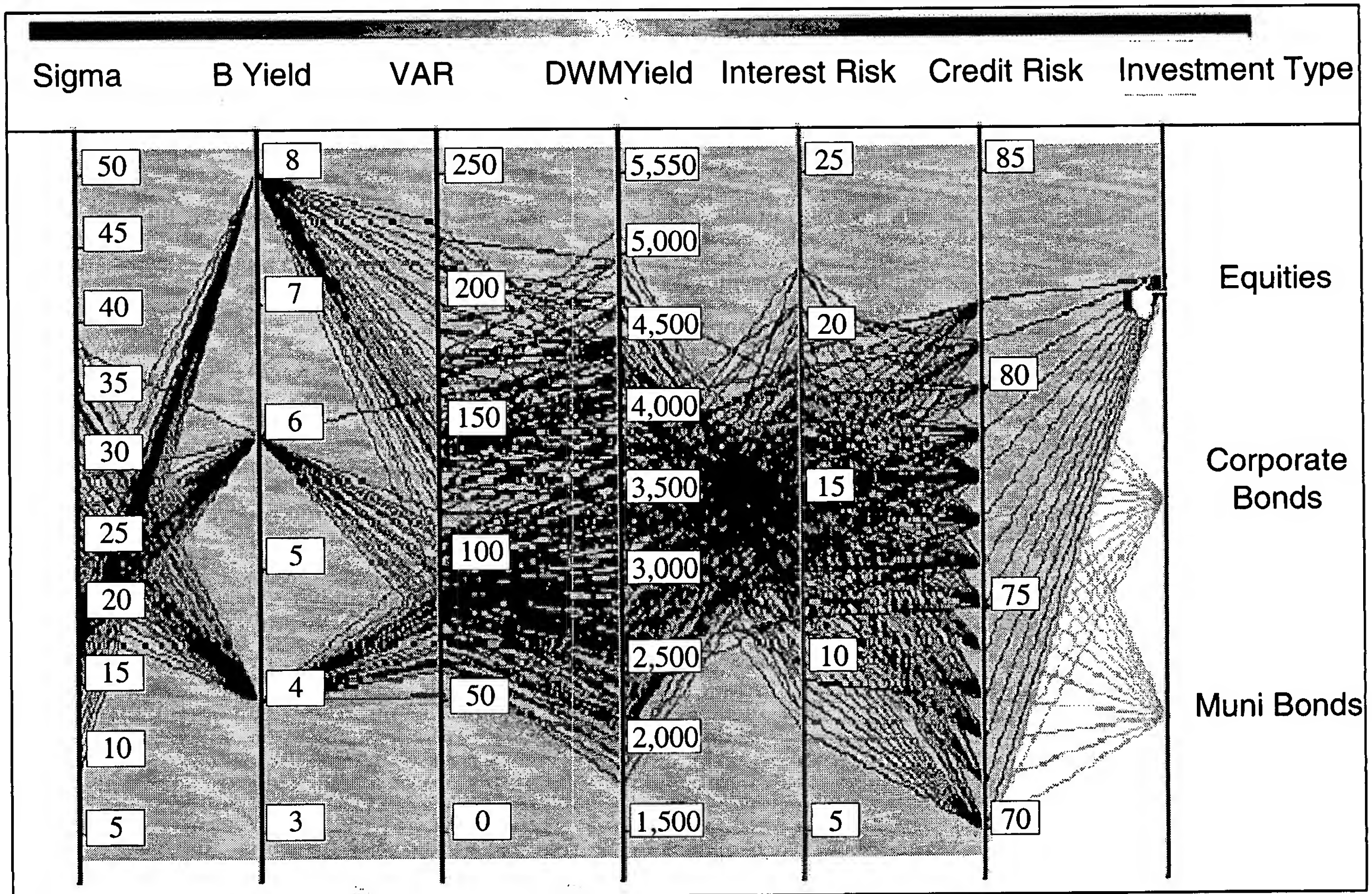
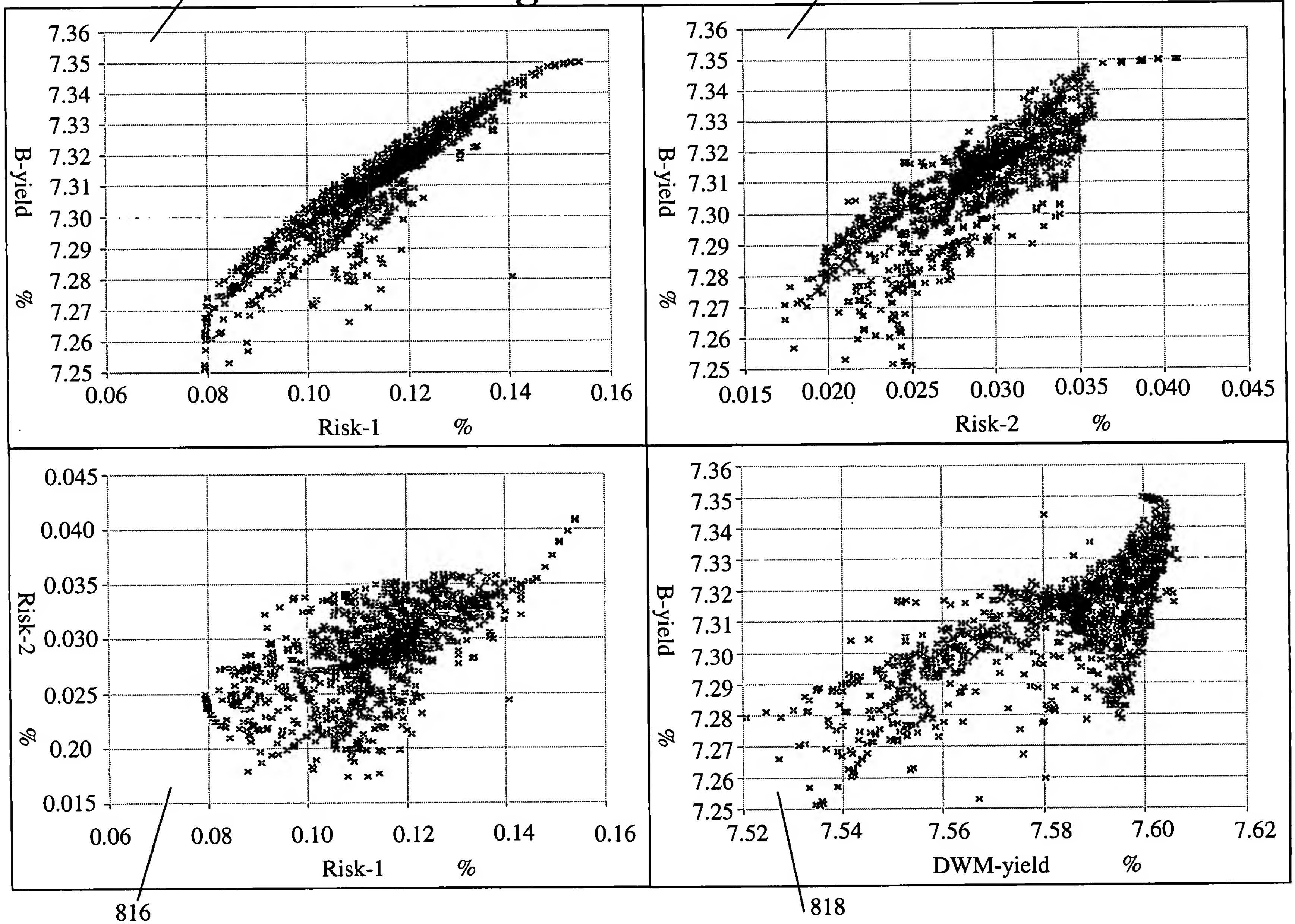


Fig. 14

Fig. 15



812
B-yield %
7.36
7.35
7.34
7.33
7.32
7.31
7.30
7.29
7.28
7.27
7.26
7.25
0.06
0.08
0.10
0.12
0.14
0.16
Risk-1 %
814
B-yield %
7.36
7.35
7.34
7.33
7.32
7.31
7.30
7.29
7.28
7.27
7.26
7.25
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Risk-2 %
816
Risk-2 %
0.045
0.040
0.035
0.030
0.025
0.20
0.015
0.06
0.08
0.10
0.12
0.14
0.16
Risk-1 %
818
B-yield %
7.36
7.35
7.34
7.33
7.32
7.31
7.30
7.29
7.28
7.27
7.26
7.25
7.52
7.54
7.56
7.58
7.60
7.62
DWM-yield %

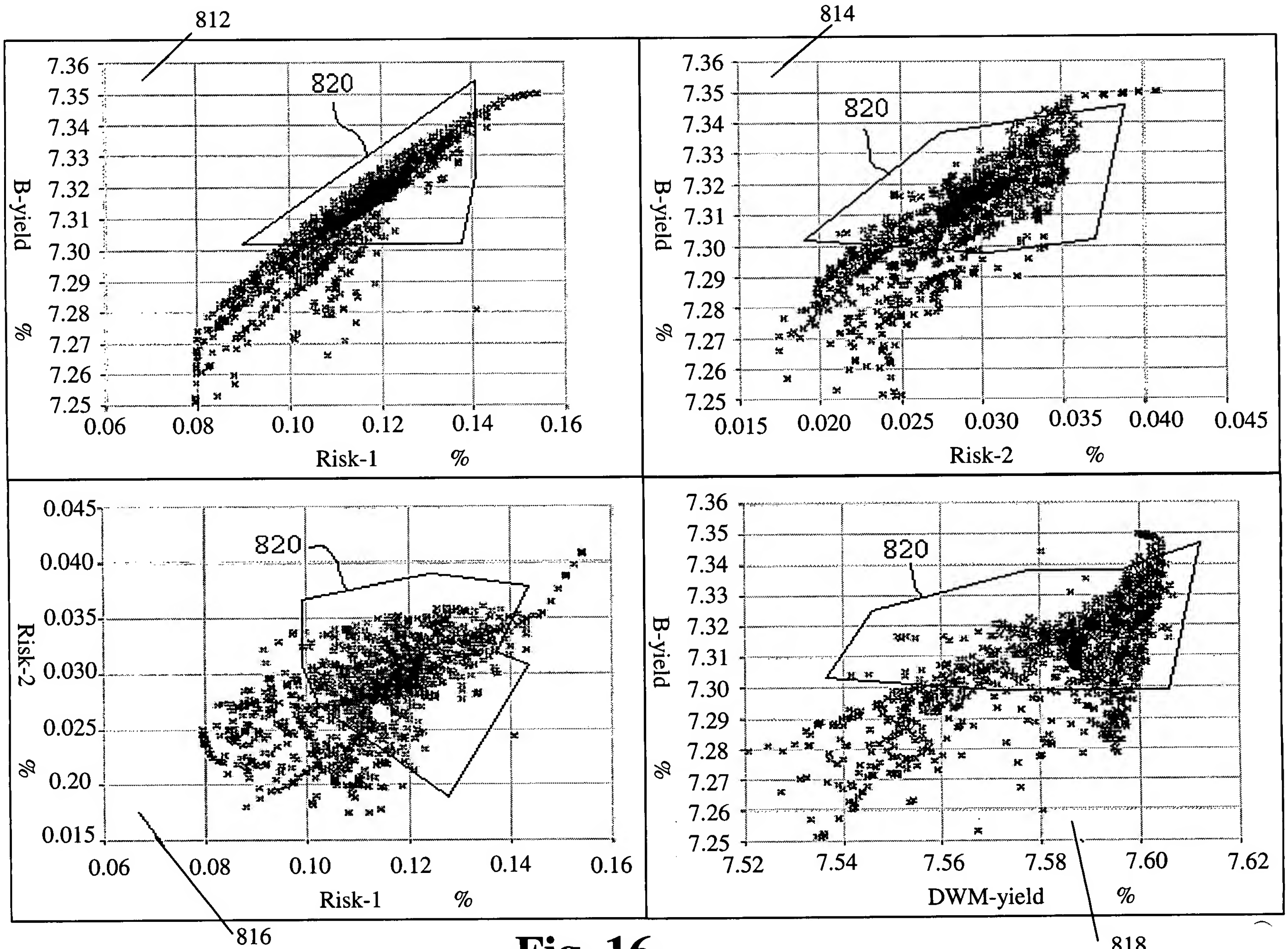

812
814
816
818
820
B-yield %
Risk-1 %
Risk-2 %
DWM-yield %
7.36
7.35
7.34
7.33
7.32
7.31
7.30
7.29
7.28
7.27
7.26
7.25
0.06
0.08
0.10
0.12
0.14
0.16
0.015
0.020
0.025
0.030
0.035
0.040
0.045
0.20
7.52
7.54
7.56
7.58
7.60
7.62

Fig. 16

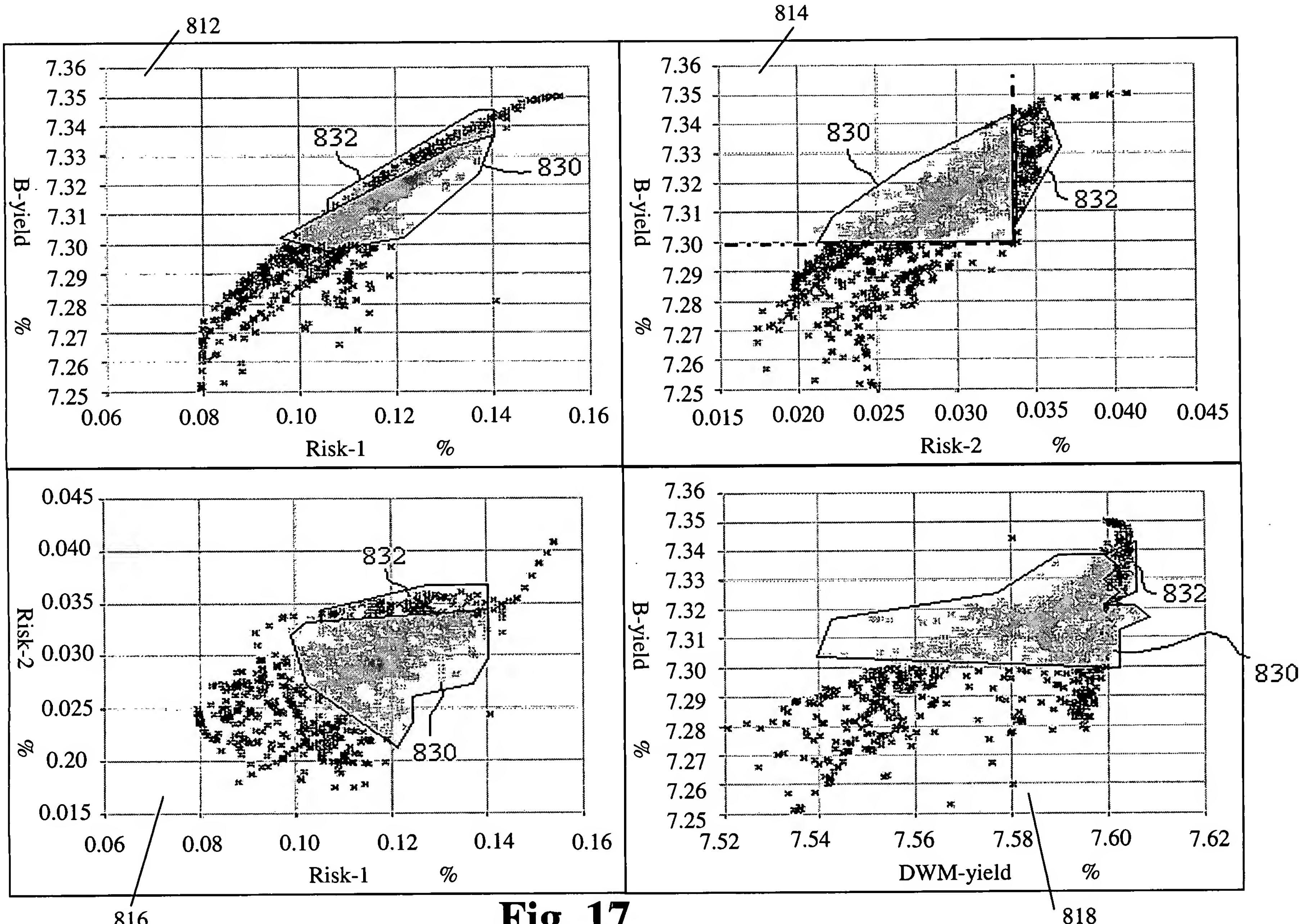

812
B-yield %
7.36
7.35
7.34
7.33
7.32
7.31
7.30
7.29
7.28
7.27
7.26
7.25
0.06
0.08
0.10
0.12
0.14
0.16
Risk-1 %
832
830
814
B-yield %
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Risk-2 %
816
Risk-2 %
0.045
0.040
0.035
0.030
0.025
0.20
0.015
818
DWM-yield %
7.52
7.54
7.56
7.58
7.60
7.62

Fig. 17

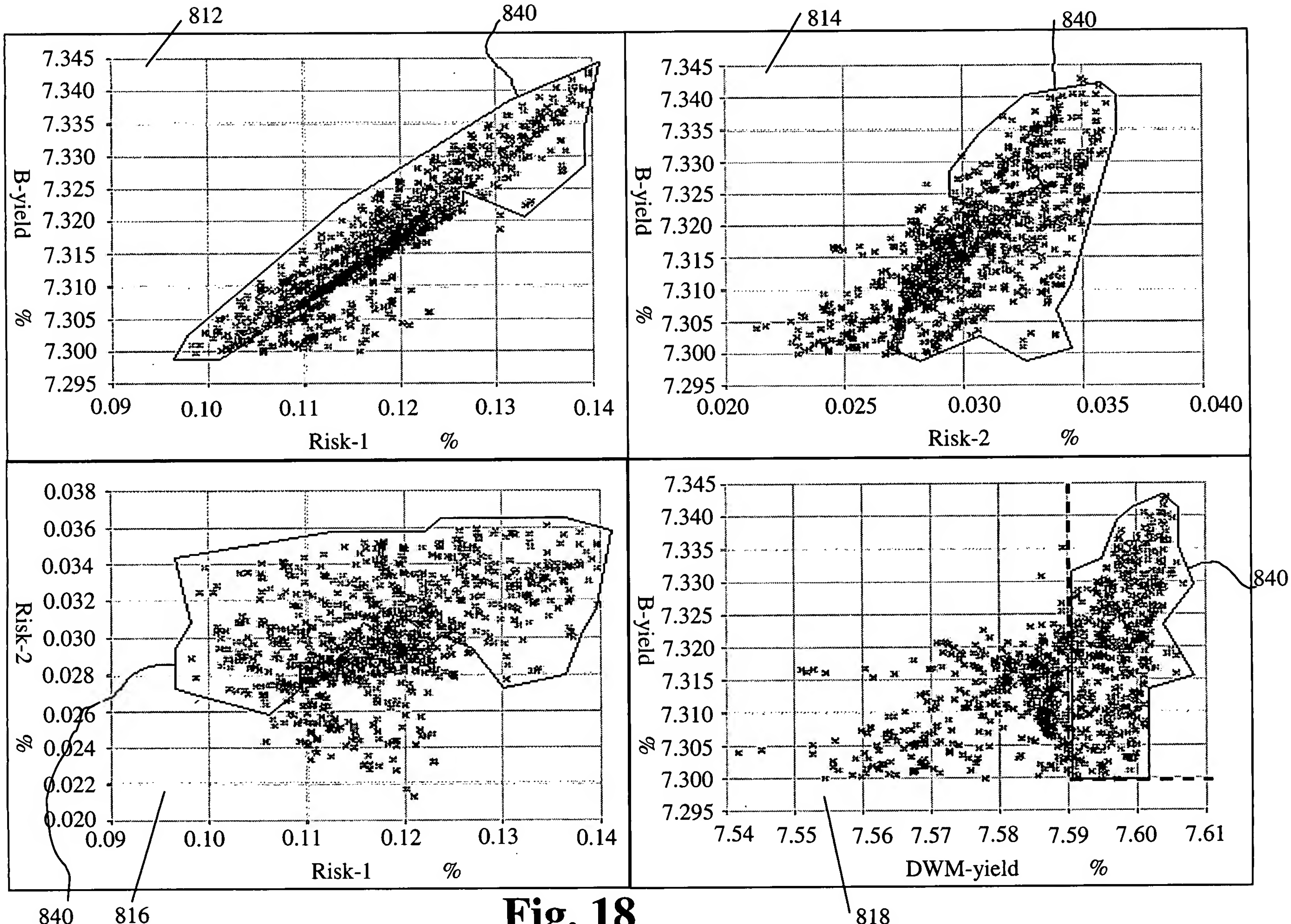

812
840
814
840
B-yield %
Risk-1 %
B-yield %
Risk-2 %
Risk-2 %
Risk-1 %
B-yield %
DWM-yield %
840
840
816
818

Fig. 18

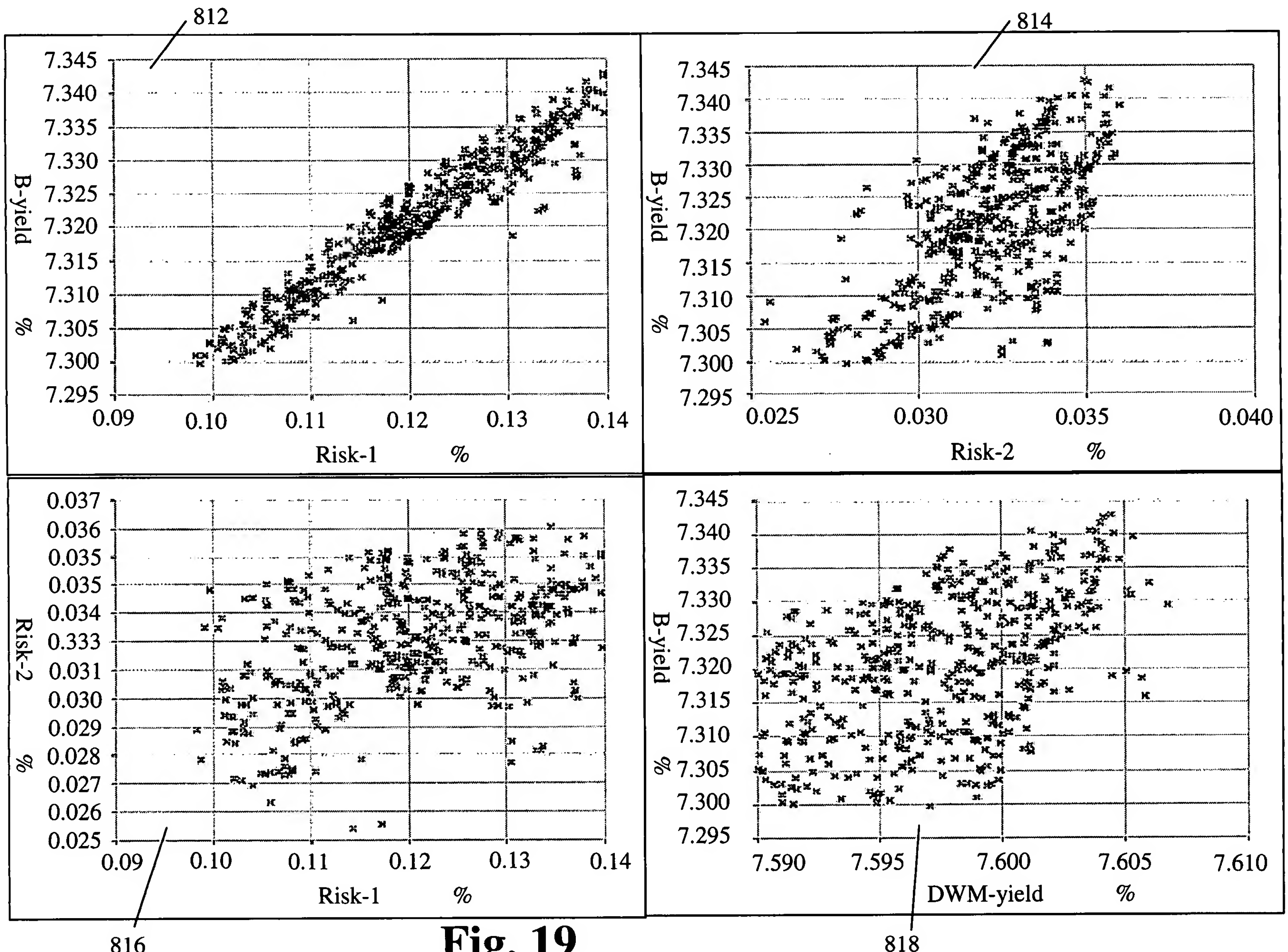

812
814
816
818
B-yield %
Risk-1 %
Risk-2 %
DWM-yield %
7.345
7.340
7.335
7.330
7.325
7.320
7.315
7.310
7.305
7.300
7.295
0.09
0.10
0.11
0.12
0.13
0.14
0.025
0.030
0.035
0.040
0.037
0.036
0.035
0.035
0.034
0.333
0.031
0.030
0.029
0.028
0.027
0.026
0.025
7.590
7.595
7.600
7.605
7.610

Fig. 19

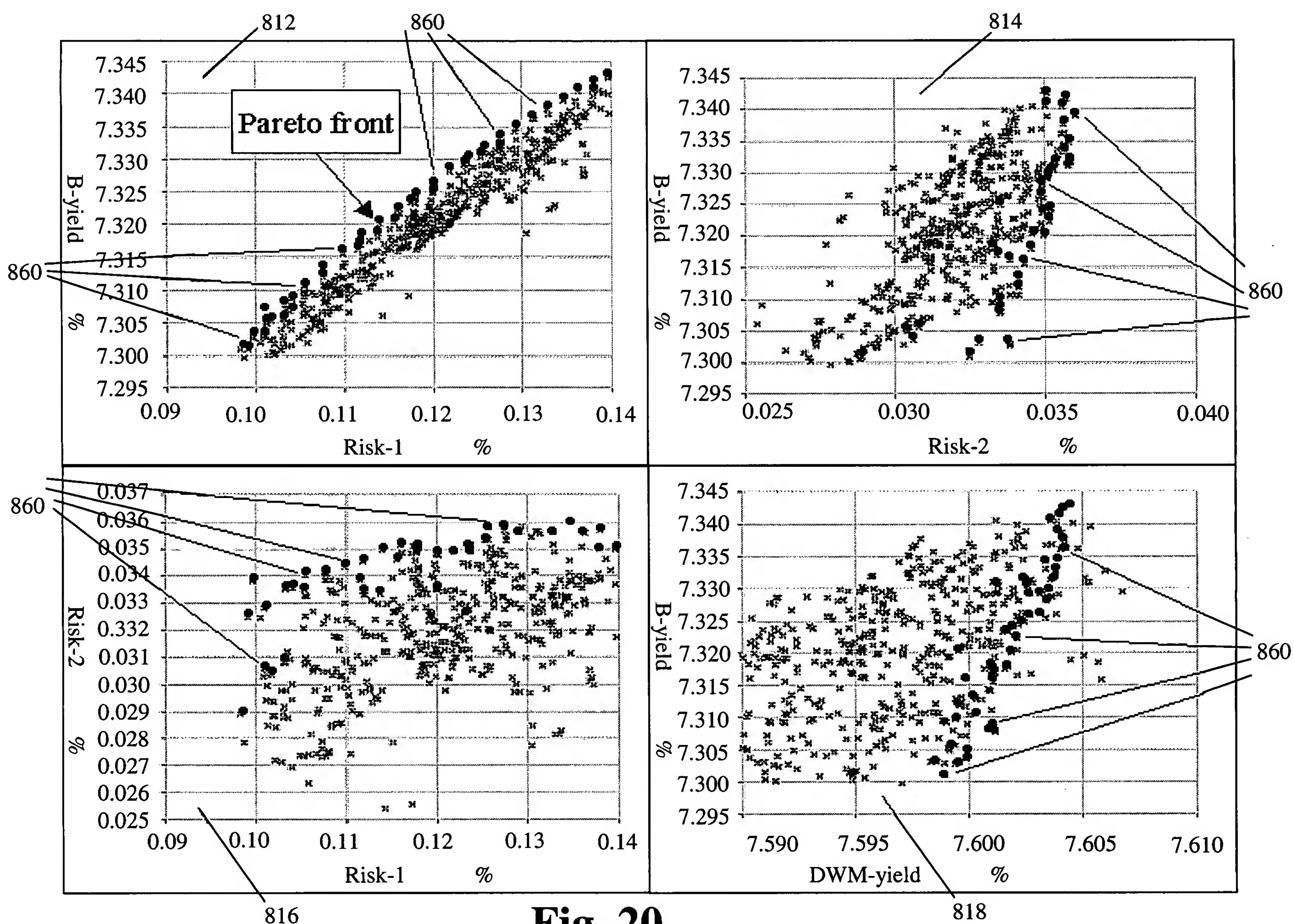

812
860
814
Pareto front
B-yield %
7.345
7.340
7.335
7.330
7.325
7.320
7.315
7.310
7.305
7.300
7.295
0.09
0.10
0.11
0.12
0.13
0.14
Risk-1 %
0.025
0.030
0.035
0.040
Risk-2 %
Risk-2 %
0.037
0.036
0.035
0.034
0.033
0.332
0.031
0.030
0.029
0.028
0.027
0.026
0.025
7.590
7.595
7.600
7.605
7.610
DWM-yield %
816
818

Fig. 20

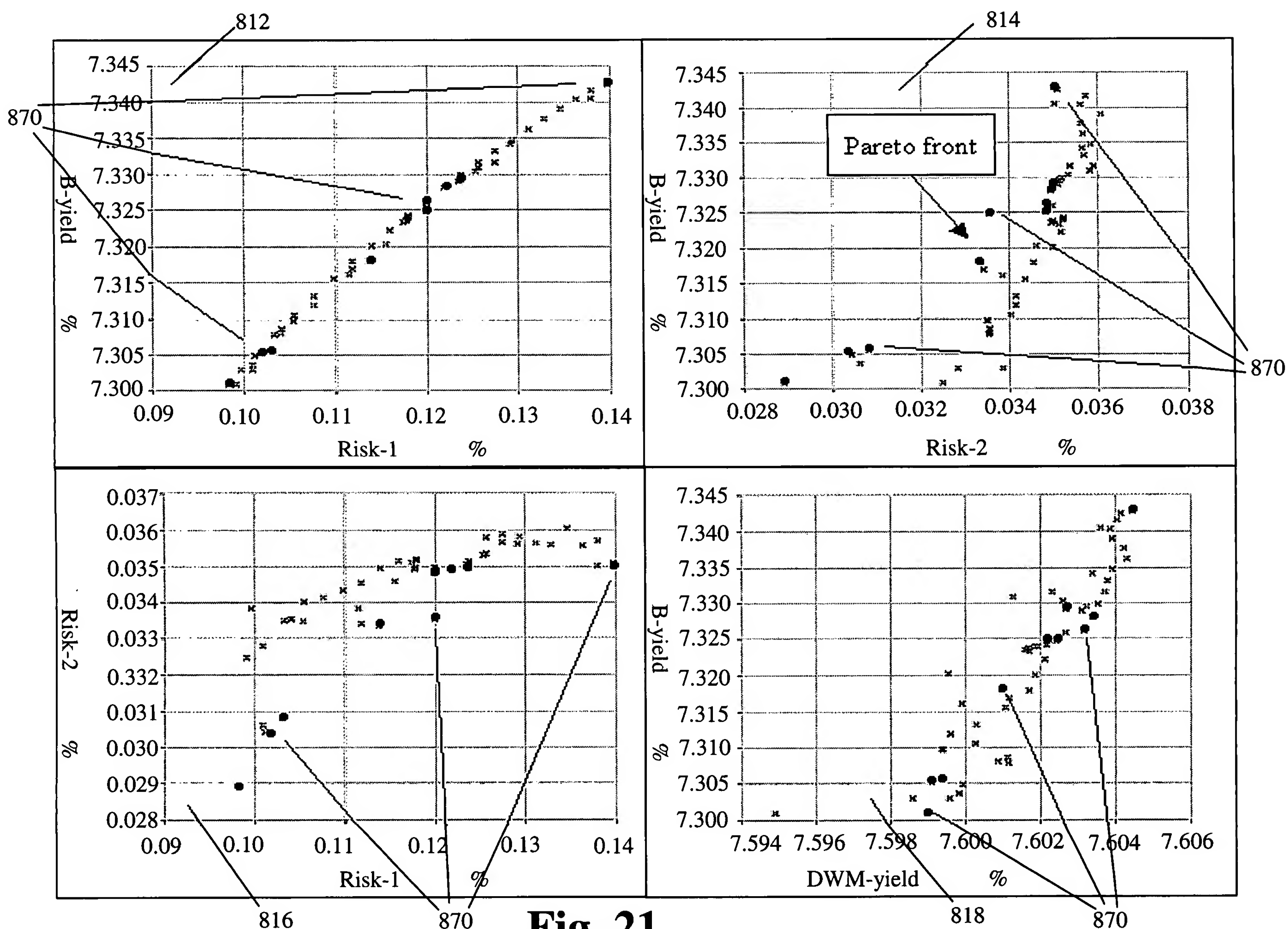
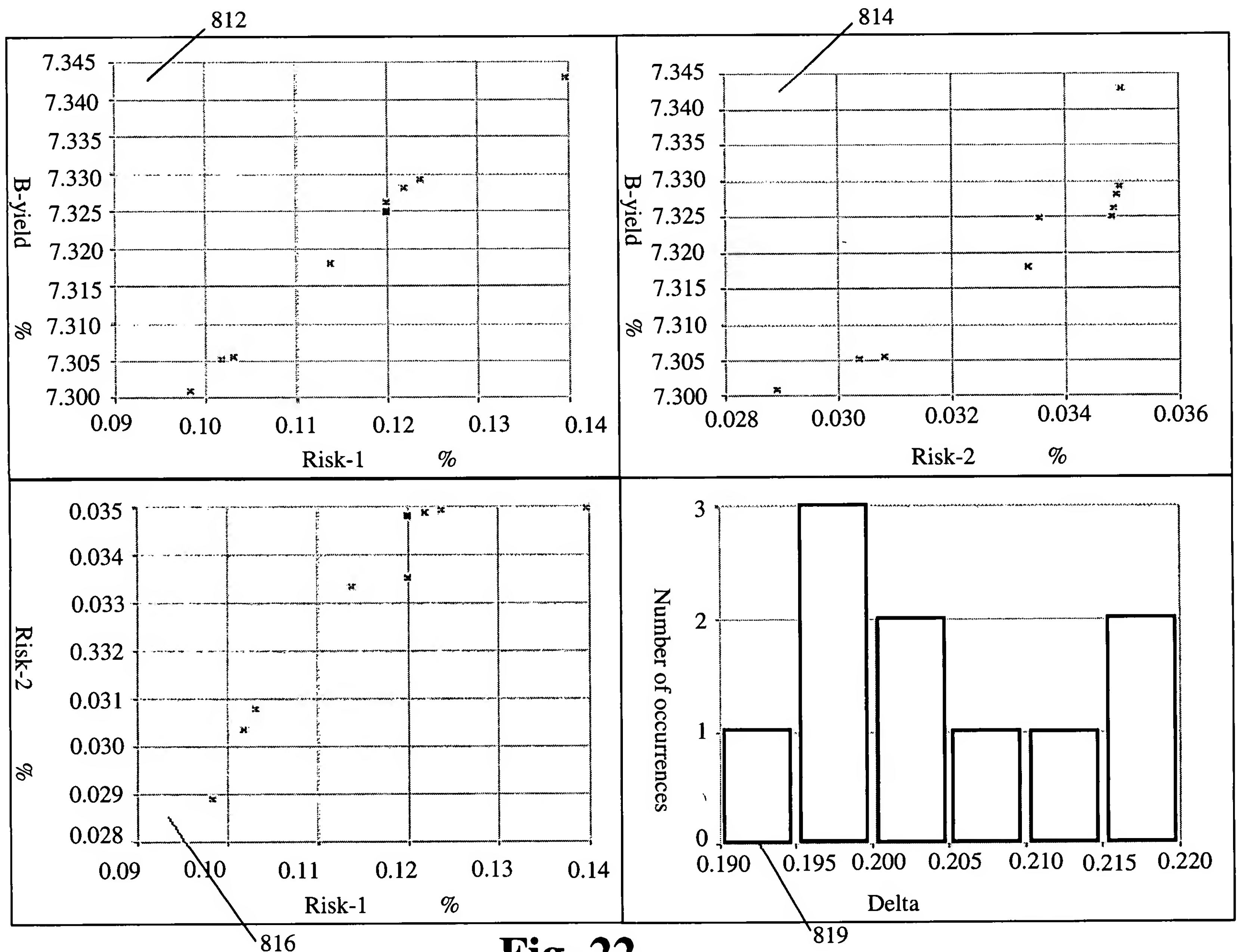

812
814
870
B-yield %
Risk-1 %
Risk-2 %
Pareto front
B-yield %
Risk-2 %
Risk-1 %
B-yield %
DWM-yield %
816
870
818
870

Fig. 21



812
814
B-yield %
7.345
7.340
7.335
7.330
7.325
7.320
7.315
7.310
7.305
7.300
0.09
0.10
0.11
0.12
0.13
0.14
Risk-1 %
0.028
0.030
0.032
0.034
0.036
Risk-2 %
Risk-2 %
0.035
0.034
0.033
0.332
0.031
0.030
0.029
0.028
816
Number of occurrences
3
2
1
0
0.190
0.195
0.200
0.205
0.210
0.215
0.220
Delta
819

Fig. 22

Feasible Regions for Optimization Figure 33

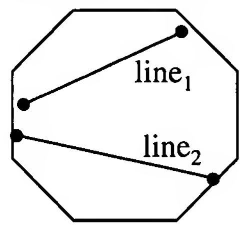
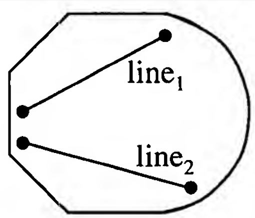
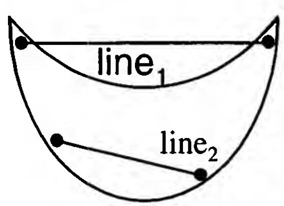
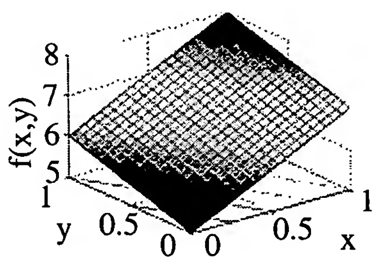
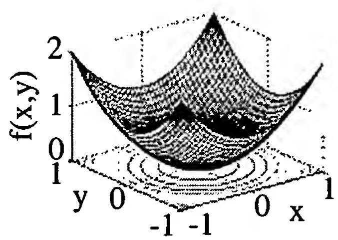
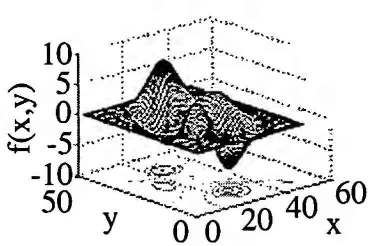
Graphic Visual	Word Description	Example Equation	GEAM
Linear Convex Space  	• For any two points in the space, the line connecting the two points is **always contained** in the same space • Space is defined using **linear** equations	$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \vdots & \vdots \\ a_{81} & a_{82} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \le \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_8 \end{bmatrix}$ **Set of linear equations**	• Market value weighted yield formulation • Duration weighted yield formulation
Nonlinear Convex Space  	• For any two points in the space, the line connecting the two points is **always contained** in the same space • Space is defined using some **nonlinear** equations	$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \vdots & \vdots \\ a_{51} & a_{52} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \le \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_5 \end{bmatrix}$ $x^2 + y^2 \le \alpha$ **Nonlinear equation**	• Interest rate sigma formulation
Nonlinear Nonconvex Space  	• For any two points in the space, the line connecting the two points is <u>not</u> **always contained** in the same space • Space is defined using some **nonlinear** equations	$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x^2 \\ x \\ y \end{bmatrix} \le \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$ **Set of nonlinear equations**	• Interest rate sigma and VAR formulation • VAR is a nonlinear nonconvex constraint

Figure 34

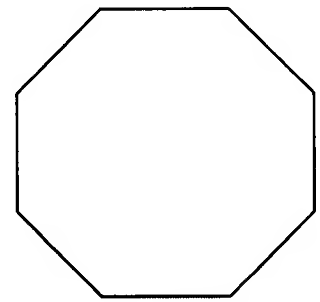
Objective Functions

Graphic Visual	Word Description	Example Equation	GEAM
Linear Function 	• Function is defined using linear equations • Straightforward math relationship • **Easy to optimize**	$f(x, y) = 2x + y + 5$	• Market value weighted yield • Duration weighted yield
Nonlinear Convex Function 	• Function is defined using a nonlinear equation • Functional gradients lead to single optimum • **Harder to optimize**	$f(x, y) = x^2 + y^2$	• Interest rate sigma
Nonlinear Nonconvex Function 	• Function is defined using **complex nonlinear equations** • Multiple local optima • Functional gradients are inefficient • **Very hard to optimize**	$f(x,y) = g_1(x,y) + g_2(x,y) + g_3(x,y) + g_4(x,y)$	• Interest rate sigma and VAR

Evolutionary Search Augmented with Domain Knowledge

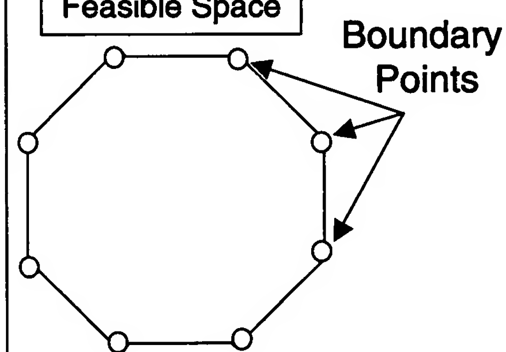
Multi-objective portfolio optimization problem is formulated as a problem with Multiple linear, nonlinear and nonlinear nonconvex objectives. However, the **domain knowledge** allows us to use strictly **linear and convex constraints.**

Linear Convex Feasible Space



Knowledge about geometry of feasible space (i.e. convexity), allowed us develop a feasible space boundary sampling algorithm (**solutions archive generation**). By knowing the boundary of the search space, we can exploit that knowledge to design efficient interior sampling methods.

Linear Convex Feasible Space



Convex crossover is a powerful interior sampling method, which is guaranteed to produce feasible offspring solutions. Given parents P_1, P_2, it creates offspring $O_1 = \lambda P_1 + (1-\lambda)P_2$, $O_2 = (1-\lambda)P_1 + \lambda P_2$. An offspring O_k and P_k can crossed over to produce more **diverse** offspring.

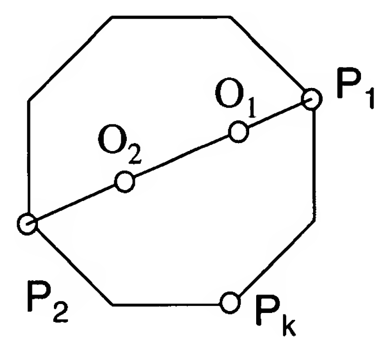


Figure 36